Lasers Can Play an Important Rôle in the Planetary Defense

C. R. Phipps
Photonic Associates

Small comet nuclei and Earth-crossing asteroids (ECA's) are much more numerous than the "Doomsday asteroids", several passing within the Moon's orbit per month. Given a calibrated force, these could be deflected in a game of "cosmic billiards" to impact and disperse a much larger object on a well-known trajectory. Lasers have the advantage of agility and calibrated force release. High-power, ground-based, repetitively-pulsed lasers will be able to accurately deflect these objects via the impulse produced by surface ablation. The thrust vector is controlled by aiming the laser at the limb of the object. Aiming is verified by comparing the centroid of the detected object with the centroid of plasma plume emission. Appropriate laser targets are those a few tens of meters in size which are detected at a range of 1-10 light seconds and actively deflected during the final light second of approach. We consider deflection of a 40-m ice NEO with 15 km/s relative velocity. We discuss optimum beam director aperture, laser wavelength, pulse energy, duration and repetitition rate, stimulated Raman scattering in the atmosphere, detection of the object, creating an adequate laser guidestar, and phasing the elements of the large beam director aperture. We consider the 265-nm – 4 μm laser wavelength range.

Introduction: what Rôle for Lasers?

The purpose of this paper is to define and explore possible rôles for lasers in the planetary defense. In earlier work for the Los Alamos Interception workshop (see Phipps 1992a, 1992b), we estimated that a ground-based laser with several GW average power would be required to deflect even the smallest near-Earth objects (NEOs) which were still large enough (40 – 80-m diameter) to penetrate the atmosphere to a depth sufficient to cause significant damage on the ground. Here, we will extend those earlier calculations to give a more accurate deflection capability assessment for lasers. To do this, we will consider the entire range of practical laser wavelengths, and include second-order effects such as the impact of pointing stability on achievable range.

In our earlier work, we also mentioned that lasers are very good at producing precise deflection of small objects passing near the Earth and we will extend that concept in this paper.

How Lasers Play in NEO Mitigation

Depending on mass density and Earth-relative velocity, precise deflection of NEO's in the 40 – 80-m diameter class is readily achieved with lasers that we can afford to build. For example, we will show that small velocity changes of order 1 mm/s are sufficient to produce changes in NEO position of order 1 earth radius at 1 AU, and that the power requirements to do this are modest.

Further, lassers are agile. A ground-based laser can follow a small NEO with sufficient precision to control the direction of the laser-induced ablation jet. The laser can also address multiple objects.

Finally, it should be kept in mind that the laser will have other uses. Large lasers are expensive, but may be justified based on multiple rôles, such as power beaming, launching payloads into LEO (See Phipps and Michaelis 1994) and obtaining rare metals by the ton from asteroid mining (Blacic 1993).

Pulsed Lasers and Momentum Coupling

The laser momentum coupling coefficient C_m is defined (by custom, in mixed units) as the ratio of momentum flux delivered to a target system to the incident laser pulse fluence. Momentum transferred is mainly due to formation of an ablation jet on the surface of the target, and only very slightly due to light pressure. Where laser fluence is constant over the target surface, W is the laser pulse energy (joules) and J is the momentum delivered by the laser-produced ablation jet (dyne-s),

$$C_m = J/W \qquad \text{dyne-s/J.} \tag{1}$$

For opaque materials in vacuum irradiated by pulsed lasers at or above plasma threshold intensity [see Phipps, *et al.* 1988], C_m is given within a factor of 2 by (see Phipps, *et al.* 1988)

$$C_m = 3.95\, M_A^{0.44}/[Z^{0.38}(Z+1)^{0.19}(I\lambda\sqrt{\tau})^{0.25}]. \tag{2}$$

The two elements of the pairs (C_m , Q^*) and (C_m , I_{sp}) are not independent, but increasing one decreases the other.

$$C_m Q^* = v_E = g I_{sp} \qquad \text{cm/s} \tag{3}$$

and
$$C_m I_{sp} = C_m{}^2 Q^* = 2 \cdot 10^7\, \eta_{AB} \tag{4}$$

where v_E is the exhaust velocity of the ablation jet, Q^* is the effective heat of mass removal (J/g), g = 980 cm/s^2 is the acceleration of gravity at Earth's surface, and η_{AB} is the efficiency with which laser energy is converted to exhaust kinetic energy. As a side comment, Eqn. (4) permits I_{sp} for laser ablation jets to achieve values much larger than those available in chemical reactions, and experimental results as large as 7,000 seconds are readily achieved (Phipps, *et al.* 1994).

Practically speaking, it is easy to obtain C_m = 5 dyne-s/J from materials such as would be found on the exposed surface of the NEO (see Figure 1, *ibid.*), given the right choice of laser intensity I, wavelength λ, and pulsewidth τ.

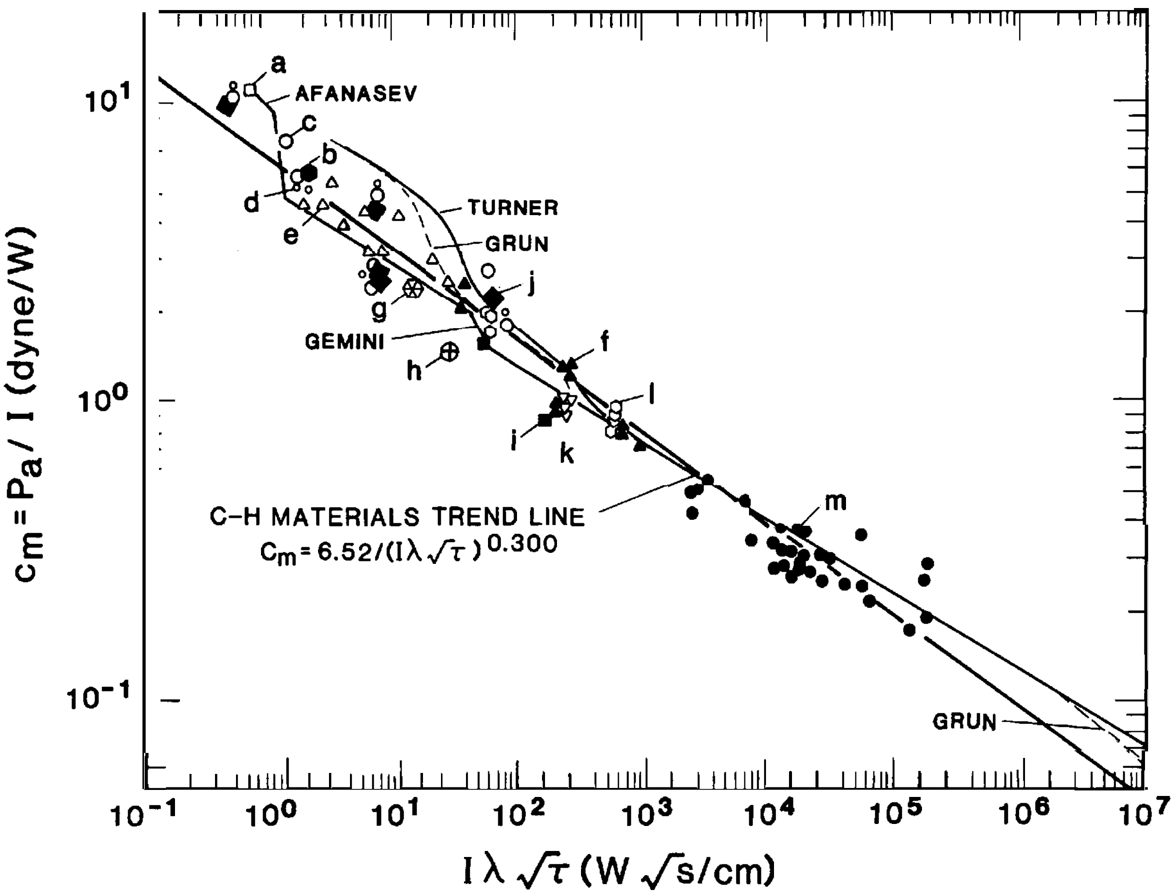

Figure 1. Compilation of experimental data for impulse coupling coefficient on C-H materials vs. the parameter ($I\lambda\sqrt{\tau}$). (a): Afanas'ev, *et al., Zhurnal Tekn. Fiz.* **39**, 894 (1969) [*Sov. Phys. Tech. Phys.* **14**, 669 (1969)], **1.5 ms, 1.06 μm on ebonite rubber**. (b): Afanas'ev, *et al., Zhurnal Tekn. Fiz.* **39**, 894 (1969) [*Sov. Phys. Tech. Phys.* **14**, 669 (1969)], **1.5 ms, 1.06 μm on carbon**. (c): Phipps, *et al.*, (unpublished), Sprite, **37 ns, 248 nm, on silica phenolic**. (d): Phipps, *et al.*, (unpublished), Sprite, **37 ns, 248 nm, on vamac rubber**. (e): Turner, *et al.*, (unpublished), **22 ns, 248 nm, on buna-n rubber**. (f): Phipps, *et al.*, (unpublished), Gemini, **1.7 μs, 10.6 μm on kevlar epoxy**. (g): Rudder, U. S. Air Force Weapons Laboratory Report AFWL-TR-74-100 (1974), **5 μs, 1.06 μm, on Grafoil.** (h): Rudder, U. S. Air Force Weapons Lab report AFWL-TR-74-100 (1974) **1 μs, 1.06 μm, on Grafoil**. (i): Phipps, *et al.*, (unpublished), Gemini, **1.7 μs, 10.6 μm on carbon.** (j): Phipps, *et al.*, (unpublished), Sprite, **37 ns, 248 nm on carbon phenolic**. (k): Phipps, *et al.*, (unpublished), Gemini, **1.7 μs, 10.6 μm on graphite epoxy**. (l): Phipps, *et al.*, (unpublished), Gemini, **1.7 μs, 10.6 μm on carbon phenolic**. (m): Grun, *et al., Phys. Fluids*, **26**, 588 (1983), **4 ns, 1.05 μ m, on C-H foils.**

Experimental data shows that the optimum target surface intensity for achieving the best coupling is (not surprisingly) just above that for plasma formation, and is given approximately for all opaque materials by (see Phipps, *et al.* 1988):

$$I_s = F\sqrt{\tau} \qquad \text{W/cm}^2 \tag{5}$$

where $F \approx 4\times10^4$ is a constant.

Continuous (CW) lasers are not indicated for the present application for two reasons. First, CW laser energy will be invested in melting the general target rather than in producing a jet at its surface. Second, in this case, melting could detonate the target, which would be catastrophic for our purposes. Furthermore, pulsed lasers allow the selection of τ and I for optimum penetration of the atmosphere.

Propagating the Pulsed Laser to the Target

The laser and beam director will be located on Earth because launching mass into orbit currently costs about \$10/g, and the benefit of locating these massive devices in space is not justified by the cost.

The earliest limit to atmospheric propagation is conversion of the laser energy to other wavelengths and propagation directions by Stimulated Raman Scattering (SRS), for which the threshold is given, for pulsewidths of interest to us, by the expression

$$I_{SRS} = D\lambda \qquad \text{W/cm}^2 \tag{6}$$

with $D = 2.83\times 10^{10}$. Denoting by A_s and A_b, respectively, the laser beam area on the target surface and within the beam near-field (in the atmosphere), Eqns. (5) and (6) are both satisfied when we pick pulsewidth and laser pulse energy according to:

$$\sqrt{\tau} = \frac{F}{D\lambda}\left(\frac{d_s}{D_b}\right)^2 \tag{7}$$

and
$$W = \frac{\pi F^2 d_s^2}{4D\lambda}\left(\frac{d_s}{D_b}\right)^2 \tag{8}$$

Using these expressions, all that is needed to compute the best τ and W for both momentum generation and SRS avoidance is to choose beam director diameter D_b and the target spot size d_s.

Target spot size comes from propagation theory, slightly modified to describe beam diameters rather than radii as in the conventional theory (see Kogelnik and Li 1966).

Where z_R is the Rayleigh Range parameter, ψ is the farfield divergence angle, d_{so} is a defined parameter, and N is the beam quality factor by which beam divergence exceeds that of a diffraction-limited beam, we can calculate d_s in all circumstances from:

$$z_R = \frac{\pi D_b^2}{8N\lambda} \tag{9}$$

$$d_{so} = \frac{D_b}{z/z_R}\left[1 - \sqrt{1 - \left(\frac{z}{z_R}\right)^2}\,\right] \tag{10}$$

$$\frac{1}{d_s^2} = \frac{1}{d_{so}^2} + \frac{1}{D_b^2} \tag{11}$$

or,
$$d_{s+}^2 = d_s^2 + [2\psi(z-z_R)]^2 \qquad \text{beyond } z_R\text{, and} \tag{12}$$

$$\psi = \frac{2\sqrt{2}\,N\lambda}{\pi D}\ . \tag{13}$$

Target flooding & Pointing limit

In addition to these considerations, we make target spot size subject to two more constraints as they become necessary:

- Spot size d_s shall not be smaller than the target (here 40m), since laser energy is most efficiently used in creating momentum when I_{opt} is achieved all over the available target surface.
- At range z, the pointing angle jitter d_s/z shall not be smaller than 50 nrad. This requirement is based on our judgments that ground-based beam pointing cannot be done with less jitter, and that laser guidestars in the sodium

layer for adaptive optics correction of the beam phase for atmospheric turbulence will not be made smaller than 50nrad x 100km = 5mm for some time.

Results for Required Pulse Energy W and Duration τ

Figure 2 following shows the results of applying all the conditions expressed in the previous two sections of this paper simultaneously, with beam director aperture as the free parameter. In the Figure, two cases are considered, namely z = 1 and 10 light-seconds. Four wavelengths are considered: 1.06μm and its second and fourth harmonic, plus 4μm (the DF laser).

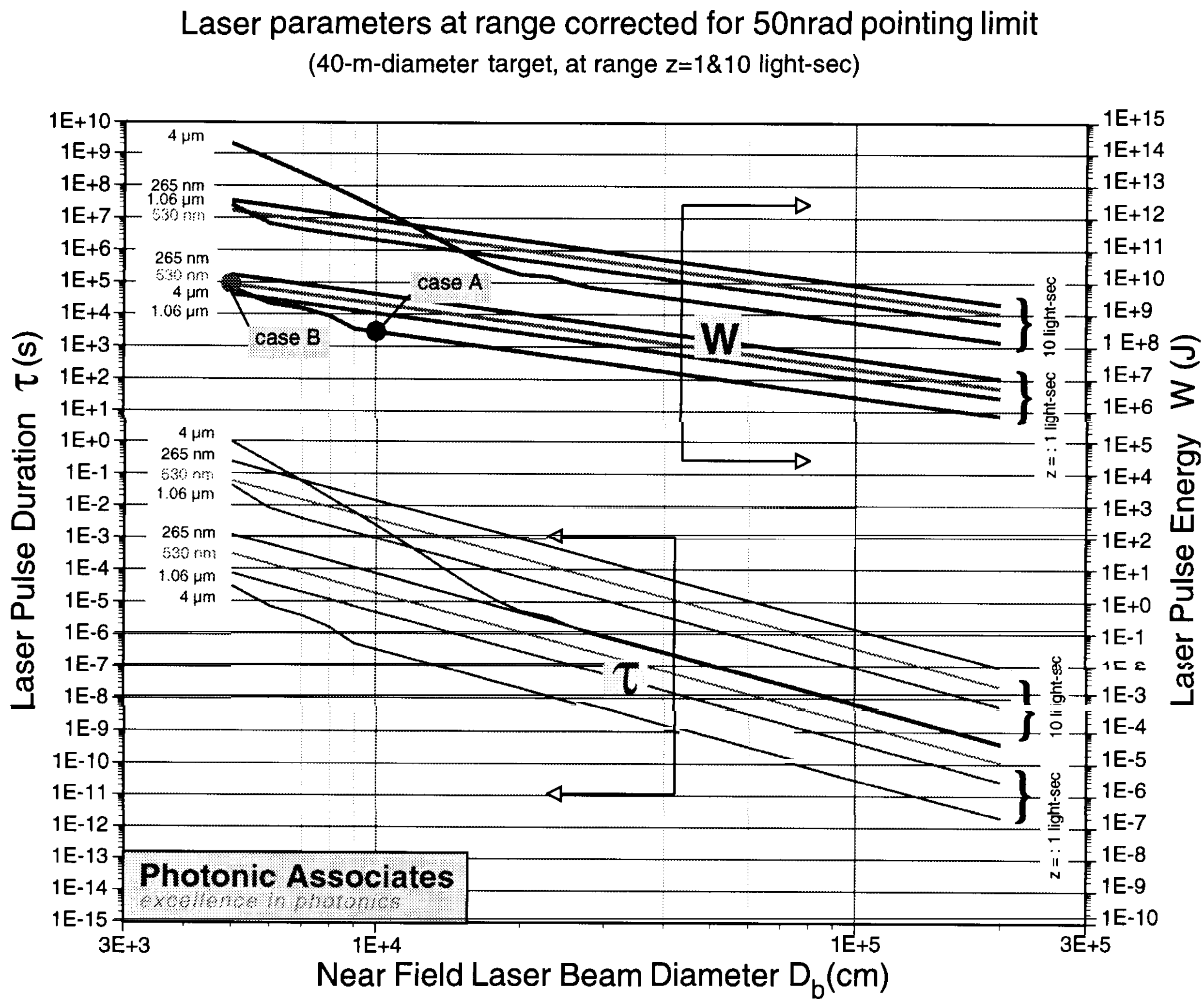

Figure 2. Laser pulsewidth τ and pulse energy W vs beam director aperture for two ranges and 4 choices of wavelength λ. Two cases are selected ("A" and "B") for further discussion.

From the graph, we pick two cases (A and B on the graph) for further consideration, based mainly on the impracticality at the present time of realizing beam director apertures larger than 50 – 100m. We note that phased element designs such as NASA's PAMELA concept might achieve such apertures with small individual mirror elements which could be built and manipulated at the bandwidth required for turbulence correction. Larger apertures will have to depend on different technology, for example, gas-density-gradient lenses (see Michaelis 1991).

These are: case A: λ = 4μm and D_b = 100m and case B: λ = 530 nm and D_b = 50m. We then use the tools in Eqns. (9) – (13) to compute optimum pulsewidth τ and pulse energy W vs. range for these two cases (Figure 3).

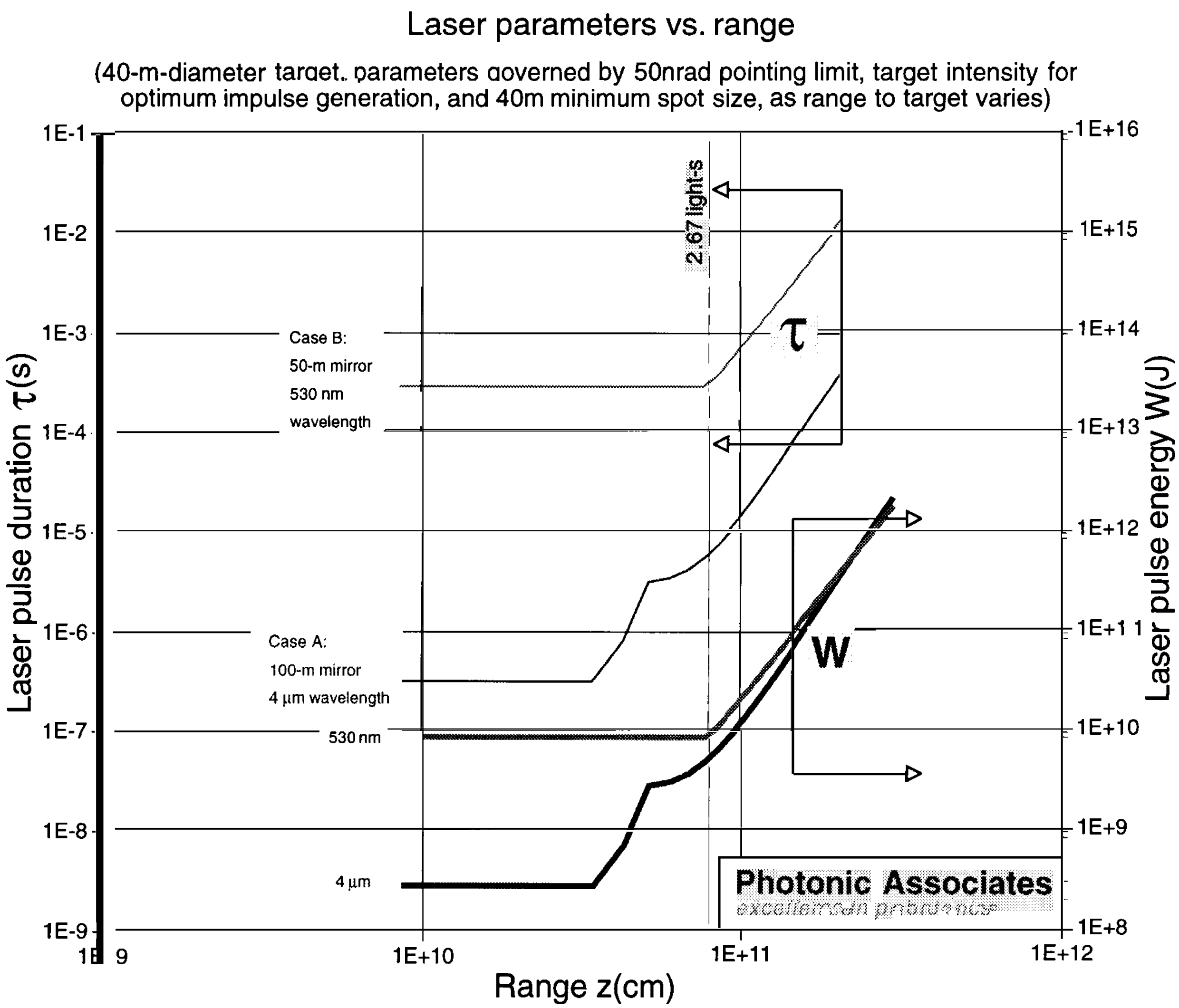

Figure 3. For cases A and B, optimum pulsewidth and pulse energy vs. NEO range are computed. Note the sharp discontinuity at z = 2.67 light-seconds. Here, N = 2 and $C_m = 5$.

Multi-GW Laser Power Needed to deflect a 40-m NEO by one Earth Radius

We found that multi-GW power level is needed to deflect even a small ice NEO approaching the Earth on a collision course with relative velocity v = 15 km/s. To obtain the plots in Figure 4, we applied the above energy to each range cell starting at acquisition range z at a rate sufficient to deflect the object by one Earth radius to obtain average power P and laser repetition frequency f.

The power minima (case B) at 2.67 light-seconds and (case A) at 2.67 and 1.7 light-seconds are artifacts of the pointing angle and spot size limitations discussed earlier as well as of the nonlinear way in which beam size varies with range, governed by propagation theory. Note that, when the NEO is closer than 1.7 light-seconds, laser power to deflect is proportional to $1/z^2$, as one might expect, since the Δv required to miss the Earth increases with decreasing time to collision, while decreasing time to act requires proportionally more power to achieve the same Δv. Laser power is roughly constant beyond a 2 - 3 light-second transition, since a progressively larger fraction of the laser beam spills over the NEO, requiring z^2 times more beam power to deliver the same power to the NEO surface, and the two range effects approximately cancel.

In any case, the laser power required is in the range 11 to 1.5 GW, depending on the wavelength chosen (4 μm or 530 nm), with a pulse energy of 6 – 9 GJ and a pulse duration of 6.5 μs or 290μs, respectively, for cases A and B. A laser with such power will cost tens of B$. The worst aspect is that, during the 15 hours between acquisition and Earth passage, more than one (probably three) laser stations will be necessary to give continuous access to the NEO.

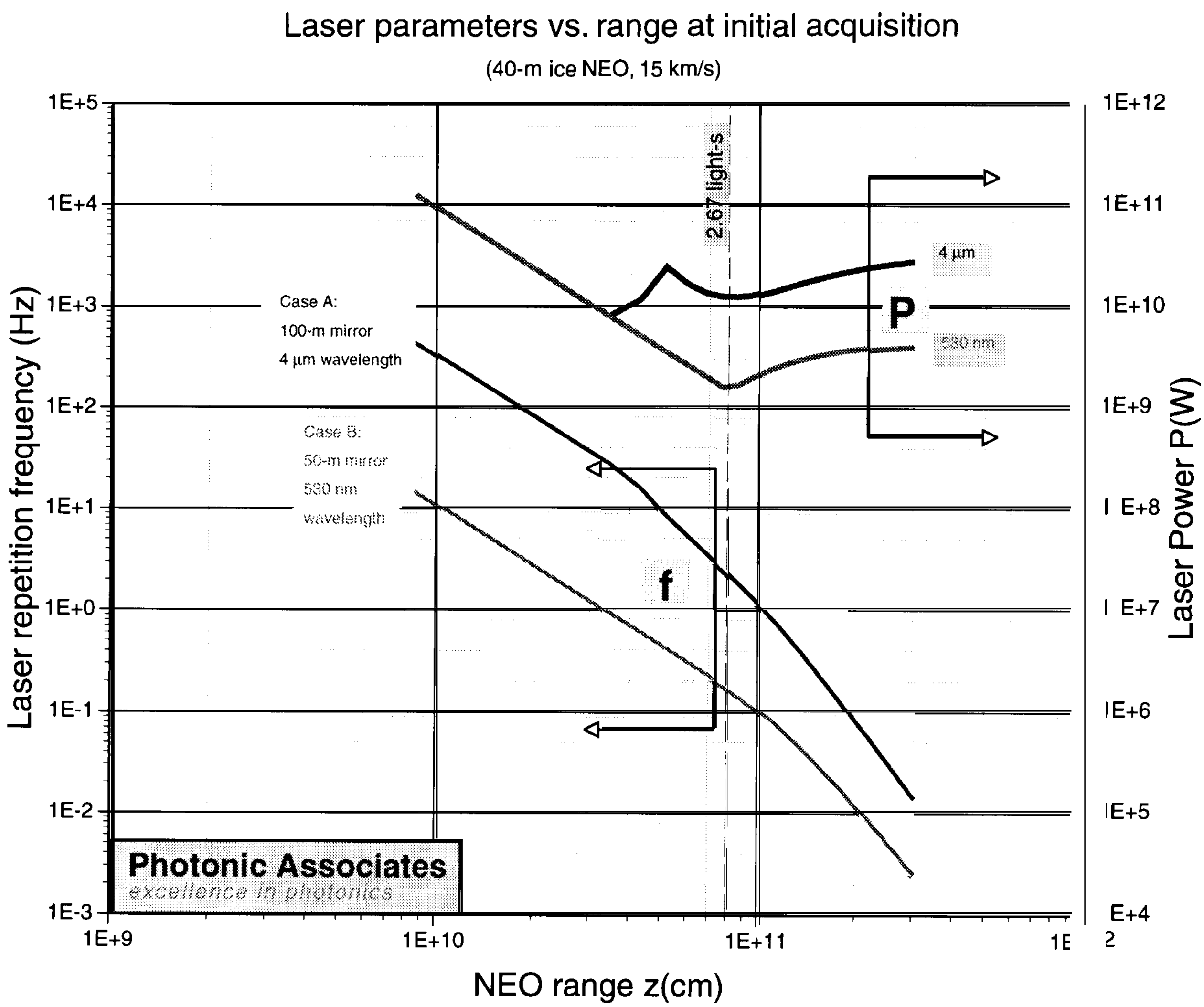

Figure 4. Laser power and frequency required to deflect a 40-m-diameter ice NEO on a collision course with Earth-relative velocity 15 km/s by one Earth radius, starting at acquisition range z. Here, N = 2 and $C_m = 5$ are assumed.

Reasonable Laser Power for Cosmic Billiards

We can use the same procedures to compute laser power required for a different problem: giving a small NEO a velocity increment of only a few cm/s, to produce relatively large position changes in the future at large range, for example, 1AU from Earth.

To assess this problem, it is only necessary to review central-force scattering theory (e.g., Goldstein 1950). The scattering angle ψ is related to the energy and velocity of the NEO at infinity (E_∞ and v_∞) and the scattering parameter b by

$$\cot\frac{\psi}{2} = \frac{2E_\infty b}{mMG} \tag{14}$$

where m and M are the mass of the NEO and the Earth, respectively, and G the gravitational constant.

The NEO will execute a hyperbolic orbit about the Earth. We wish to know what velocity increment δv (applied by laser near the point of closest approach to Earth) will produce a future transverse displacement $\delta z_\perp = z\delta\psi$ of NEO position after it has passed the Earth and gone out to range z. Differentiating Eqn. (14) and allowing a factor of 2 to account for the fact that we can modify the NEO trajectory over only half of the scattering event (after near-Earth passage) we obtain:

$$\frac{d\psi}{dv_\infty} = -4\sin^2\frac{\psi}{2}\frac{bv_\infty}{MG} \quad (15)$$

We take $\psi = \pi/2$, $v_\infty = 15$ km/s, MG = $3.988\mathrm{x}10^{20}$, and b = 1 light-second to find that

$$\delta v_\infty = 0.19\ (\delta z_\perp / R_E)(z/1\mathrm{AU})\ \mathrm{cm/s} \quad (16)$$

For example, a 1.9 cm/s velocity change during near-Earth passage is sufficient to produce a 10 Earth-radius (R_E) shift of NEO position at z = 1AU.

Using the previously described analysis for power vs. range, we obtain the following results for the "cosmic billiards problem", using as a cue-ball a 40-m diameter object of density 0.97 (ice) or 9.0 (iron) with 15 km/s Earth-relative velocity. We consider the same best acquisition range (2.67 light-seconds) and laser wavelengths (530 nm & 4μm) as before.

Table 1. Laser Power for NEO Position Shift at 1AU range after Earth passage

	Average Power for Position Shift			
NEO	**530 nm,10 R_E**	**4 μm,10 R_E**	**530 nm,100R_E**	**4 μm,100 R_E**
40-m ice	230 kW	1.7MW	2.3 MW	17 MW
40-m iron	2.1 MW	15 MW	21 MW	150 MW

Conclusions

We have shown that lasers of relatively modest power (230 kW) are capable of precisely deflecting a 40-m ice NEO during near-Earth passage by an amount sufficient to produce a future shift in position of 10 Earth radii at a range of 1AU, in order to engage in a game of cosmic billiards with a much larger Earth-threatening object whose position is known well in advance. Such capabilities are unique to lasers among the devices which have been discussed for NEO deflection. Such a laser could be used for other purposes, as well.

Acknowledgment

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